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An Efficient Beam Training Technique for mmWave Communication Under NLoS Channel Conditions

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***Abstract*—An efficient codebook-based beam training technique is proposed for mmWave communication systems operating under non-line-of-sight (NLoS) channel conditions. Using convex optimization theory, this technique formulates the beam training process as a combinational optimization problem. It finds the best transmit-receive beam pair that maximizes the received signal power by iterating the Nelder-Mead simplex method through a multi-stage formulation of the training process. Compared with beamforming protocols adopted by 60 GHz WLAN/PAN systems, the proposed technique is robuster in NLoS scenarios. Simulation results demonstrate that the proposed technique achieves the same selection performance as the exhaustive search with a possibility of 87.6% while requiring moderate measurement steps.**

I. Introduction

The unlicensed spectrum in mmWave bands enables multi-Gbps data rates and motivates several standardization activities [1], [2]. To benefit from the extensive frequency resource of up to 9 GHz, developments on low-cost and low-power transceiver structures along with efficient beamforming techniques or protocols are required for mmWave communication systems [3].

To compensate for the large propagation loss in mmWave channels, the use of high-gain directional arrays has been proposed. Fortunately, the short wavelength makes it possible to have a physically small array with large numbers of antenna elements. Another challenge concerns the beamforming techniques to be adopted. For systems operating at microwave frequency, multiple-input multiple-output (MIMO) techniques are widely used to increase data rate. These techniques require multiple radio frequency (RF) chains to support spatial multiplexing, however this complicates the transceiver structure. Due to the RF hardware constraints, conventional full order MIMO techniques are impractical for mmWave systems with large arrays. Instead, beamforming techniques which simplify the transceiver structure and improve the transmission range are employed.

Several codebook-based beamforming techniques have been proposed in [4]–[7] to overcome the mmWave hardware limitations. The key idea is to restrict the antenna weight coefficients to a small number of low-resolution phase shifts and to jointly select the best pair from the transmitter and receiver. Principal techniques adopted by 60 GHz WLAN/PANs are the "codebook-based protocol" from IEEE 802.15.3c standard [1] and the "iterative method" from IEEE 802.11ad standard [2].

The Beamforming techniques proposed in [6]–[8] formulated the training process as optimization problems. These techniques find the best beam pair that maximizes the link quality using various numerical algorithms. With reduced search scope, these techniques require shorter training duration compared with state-of-the-art strategies. A fast beam switching technique presented in [6] solves the training problem using a novel initialization scheme followed by the classic Rosenbrock algorithm. To further improve the search accuracy, the work in [7] describes a BF technique inspired by the simulated annealing mechanic. This technique employs a novel two-level temperature adjustment scheme to identify the global optimum on the objective function. In [8], an efficient and low-complexity beam training technique is proposed, which solves the training problem in LoS scenarios using the Nelder-Mead simplex method.

In this paper, an analogue beam training technique is proposed for mmWave systems operating under NLoS channel conditions. The technique formulates a multi-stage beam training process as a combinational optimization problem and finds the optimal beam pair using the Nelder-Mead simplex method. Compared with beamforming protocols adopted by 60 GHz WLAN/PAN standards, this technique improves the performance robustness against NLoS channels. By adjusting the value of certain parameters, a desirable trade-off between the training accuracy and complexity is achieved.

II. System Model

A. Beamforming Model

The typical beamforming model consists of a transmitter with M_t antennas and a receiver with M_r antennas. At the transmitter, the baseband signal is up-converted to radio frequency and weighted at each antenna via the beamforming vector w_t. After propagating through a multipath MIMO channel, signals at the receiver are combined using the beam combining vector w_r, before being down-converted for baseband processing. The antenna weight vectors, w_t and w_r, are selected to optimize a chosen link quality metric, which, in this paper, is the received signal power.

B. Beamforming Codebook

A beamforming codebook is an $M \times K$ matrix W, where M and K are the number of antenna elements and beam patterns respectively. Each column of the matrix W defines an antenna weight vector, specifying a beam pattern. To simplify the transceiver structure and minimize its power consumption, the codebook considered in this paper applies only four phase shifts, i.e., 0°, 90°, 180° and 270°, without amplitude adjustment, to each antenna [4], [9]. This codebook has been adopted by IEEE 802.15.3c standard [1]. The $(m,k)-th$ entry of the codebook matrix W is:

$$\begin{gathered} W(m,k) = j^{floor\{\frac{m\times mod(k+(K/2),K)}{K/4}\}}, \\ m = 0,\cdots,M-1; \quad k = 0,\cdots,K-1; \end{gathered} \tag{1}$$

where the function $floor(x)$ returns the biggest integer smaller than or equal to x. The function $mod(x,y)$ returns the integer equal to $(x-zy)$, with $z = floor(x/y)$.

For a uniform linear array (ULA) with antenna separation of d, weighted by the $k-th$ column vector of the codebook matrix W, the array factor is calculated as:

$$AF_k(\phi) = \frac{1}{\sqrt{M}}\sum_{m=0}^{M-1} W(m,k)e^{j2\pi m(d/\lambda)\sin(\phi)}, \tag{2}$$

where λ is the wavelength and ϕ denotes the polar angle with respect to the x-axis, given that the array lies along the y-axis.

C. Channel Modelling

Standard indoor channel models for 60 GHz WLANs are used in this paper to evaluate the performance of the proposed beam training technique. The channel model is described in detail in IEEE 802.11ad standard [10] and were previously used to evaluate performance in LoS conditions in [8].

Considering the temporal-spatial parameters of the channel model along with beam patterns specified by the codebook matrix W, the received signal power is derived as:

$$\begin{aligned} S(p,q) = \sum_i \sum_l |([E_t^V \quad E_t^H]H^{(i,l)}[E_r^V \quad E_r^H]^T) \\ AF_p(\phi_t^{(i,l)})AF_q(\phi_r^{(i,l)})|^2, \end{aligned} \tag{3}$$

where p and q index the antenna weight vectors chosen from the transmit and receive codebooks respectively; $H^{(i,l)}$ and $\phi_t^{(i,l)}$, $\phi_r^{(i,l)}$ denote the complex gain (with polarization characteristic support) and angular coordinates of the $l-th$ ray within the $i-th$ cluster; $[E_t^V \quad E_t^H]$ and $[E_r^V \quad E_r^H]$ are polarization vectors of individual antennas at the transmitter and receiver respectively.

III. Related Works on Beamforming Protocol for 60 GHz WLAN/PANs

To find the best pair of beam patterns with a given resolution between the transmitter and receiver, several codebook-based beamforming techniques have been reported for 60 GHz WLAN/PAN systems. This section reviews beamforming protocols adopted by IEEE 802.15.3c and IEEE 802.11ad standards, which will be compared with the proposed beam training technique in section V.

A. "Codebook-based Protocol" adopted in IEEE 802.15.3c

This protocol supports three kinds of beam patterns, namely, the "quasi-omni pattern", "sector" and "beam", ranked by increasing resolution. The protocol minimizes the required steps of measurement by dividing the beam training process into multiple stages. The first stage, "device-to-device linking", performs an exhaustive search among all pairs of quasi-omni patterns between the transmitter and receiver in order to find the best. "Sector-level searching", the second stage, explores sector pairs mapped within the chosen quasi-omni patterns. Following that is the final stage, "beam-level searching", which refines and outputs the best pair of transmit and receive beams within the selected sectors.

B. "Iterative Method" adopted in IEEE 802.11ad

The beamforming protocol adopted in IEEE 802.11ad standard, [2], [5], consists of two phases, named "sector-level sweep (SLS)" and "beam refinement protocol (BRP)". The former sweeps all sectors at the transmitter one by one while setting the receiver in quasi-omni mode in order to find the optimal transmit sector. The latter is composed of, at least, two "beam refinement transaction (BRT)" sub-phases. Steering the transmitter to the sector selected in SLS, the first BRT scans entire receive beams to find the best. The second BRT sweeps part or complete transmit beams while steering the receiver to the beam chosen in the previous stage. These two sub-phases are iterated for a number of times to output the best beam pair between the transmitter and receiver.

IV. Nelder-Mead-based Beam Training Techniques

Using convex optimization theory, the codebook-based beam training process is formulated as a combinational optimization problem. The joint selection of optimal antenna weight vectors at transmitter and receiver has been efficiently solved using numerical techniques, such as the Rosenbrock algorithm [6], the simulated annealing mechanism [7] and the Nelder-Mead simplex method [8].

A. Formulation of Codebook-based Beam Training Problem

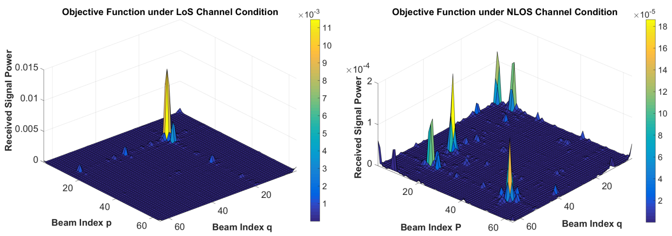
Given Equation 3, the received signal power, under the quasi-static channel assumption, depends solely on the antenna weight vectors chosen from the transmit and receive codebooks. This facilitates formulating the beam training process as a combinational optimization problem where the optimal beam pair maximizing the objective function, i.e., the received signal power, is found among feasible pairs of transmit-receive beams (p,q) using numerical algorithms. This optimization problem is formulated as:

$$(p,q)_{opt} = \max_{(p,q)} S(p,q), \tag{4}$$

where $p,q = 1,\cdots,K$. Fig. 1 shows an example of the objective functions created under LoS and NLoS channel conditions respectively.

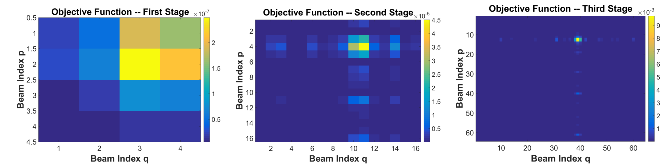
B. The Nelder-Mead-based Beam Training Technique

The Nelder-Mead simplex method was first proposed in [11] and reviewed in [8], which is applicable to the minimization or maximization of a function of n variables. For the maximization case, this method tracks the optimum by comparing function values at the $(n+1)$ vertexes of a general simplex and then replacing the vertex with the lowest value by another point. This method depends neither on gradients nor



(a) (b)

Fig. 1: The objective function created for (a) LoS and (b) NLoS scenarios with $M = 32$ and $K = 64$ at both the transmitter and receiver



(a) (b) (c)

Fig. 2: Objective functions formed for LoS scenarios with (a) $M = 2$ and $K = 4$, (b) $M = 8$ and $K = 16$, and (c) $M = 32$ and $K = 64$ at both the transmitter and receiver

on quadratic forms of the objective function and, therefore, is computationally compact and tractable.

The Nelder-Mead method always adapts itself to a local landscape. On meeting objective functions containing irregular variations on the surface, this method may falsely converge to a point other than the global optimum. For the objective functions shown in Fig. 1, a randomly initialized simplex may contract on to a local maximum, outputting a received signal power far lower than the desired value. To avoid such erroneous contractions, the beam training technique proposed in [8] iterates the Nelder-Mead simplex method through a multi-stage beam training process which sequentially evaluates the beams of increased resolution.

The first stage of the Nelder-Mead-based beam training technique [8] forms an objective function with a convex surface, as shown in Fig. 2a, using beams of low-resolution at both transmitter and receiver. The requirement of such a convex function is to guarantee that the Nelder-Mead simplex method tracks down to the optimal beam pair with high accuracy and efficiency. In the following stages, by sequentially increasing the resolution of the beams, new objective functions with non-convex surfaces are formed, as shown in Fig. 2b and 2c. The vertexes of the initial simplex are then derived, using the concept of small region dividing and conquering [6], from beam indexes selected in the previous stage to ensure a sensible convergence of the Nelder-Mead algorithm.

For a symmetric beamforming model where both transmitter and receiver have $M = 32$ antennas together with the codebook designed by Equation 1, the optimal beam pair is found using the following procedures:

1) Stage 1:

- Activate $M^1 = 2$ antennas and create $K^1 = 4$ beams using Equation 1; Index beams from the transmitter and receiver by p^1 and q^1 respectively.
- Define the three vertexes of the initial simplex as points: $P_1^1 = (p_1^1, q_1^1)$, $P_2^1 = (p_1^1 + sl_2^1, q_1^1)$ and $P_3^1 = (p_1^1, q_1^1 + sl_3^1)$, where $p_1^1 = q_1^1 = 3$, sl_2^1 and sl_3^1 are separately assigned either 1 or -1 whichever maximizes the function value at points P_2^1 and P_3^1.
- Note that this adaptive initialization guarantees that the simplex orientates upward the maximum point on the objective function.
- Start the Nelder-Mead simplex method; Have the vertexes of the initial simplex replaced, guided by the three operations: reflection, expansion and contraction, described in [11].
- Track the contraction point, $P_{con}^1 = (p_{con}^1, q_{con}^1)$, of the Nelder-Mead method; Explore points $(p_{con}^1 \pm 1, q_{con}^1)$, $(p_{con}^1, q_{con}^1 \pm 1)$ and then select the optimum as the one with the highest function value: $P_{opt}^1 = (p_{opt}^1, q_{opt}^1)$.

2) Stage 2:

- Quadruple active antennas along with beams at both transmitter and receiver, with $M^2 = 8$ and $K^2 = 16$.
- Start the Nelder-Mead method with a simplex defined by points $P_1^2 = (p_1^2, q_1^2)$:

$$\begin{aligned} p_1^2 &= 2 \times (2 \times p_{opt}^1 - 1) - 1, \\ q_1^2 &= 2 \times (2 \times q_{opt}^1 - 1) - 1, \end{aligned} \tag{5}$$

  $P_2^2 = (p_1^2 + sl_2^2, q_1^2)$ and $P_3^2 = (p_1^2, q_1^2 + sl_3^2)$, where sl_2^2 and sl_3^2 are separately assigned either 2 or -2, whichever gives the highest function value.
- Note that Equation 5 uses the concept of small region dividing and conquering [6] to ensure that the simplex is always initialized in the neighborhood of the optimum selected in the previous stage.
- Implement operations in stage 1 item 4 to output the optimal point, $P_{opt}^2 = (p_{opt}^2, q_{opt}^2)$.

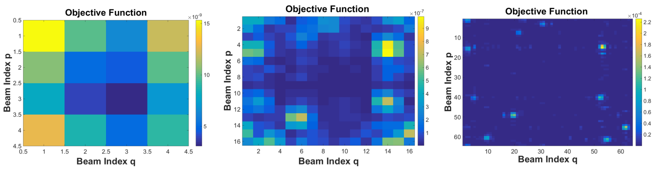
3) Stage 3:

- Repeat operations from stage 2 to find the optimal point, $P_{opt}^3 = (p_{opt}^3, q_{opt}^3)$, where p_{opt}^3 and q_{opt}^3 index beams with a given resolution ($M^3 = 32$ and $K^3 = 64$) chosen from the transmit and receive codebooks respectively.

C. The Modified Nelder-Mead-based Beam Training Technique

The Nelder-Mead-based beam training technique evaluates only part of the entire beam pairs in each stage, solving the beam training problem efficiently. This technique achieves a desirable performance in LoS scenarios [8], where the optimum, arising from the direct path between the transmitter and receiver, has a dominant function value, as shown in Fig. 2. However, in NLoS scenarios, many propagation rays may have comparable amplitudes, giving rise to an objective function containing multiple local optima, as shown in Fig. 1b.

Under such unfavorable conditions, the low-resolution beams used in the first stage of this beam training technique



(a) (b) (c)

Fig. 3: Objective functions formed for NLoS scenarios with (a) $M = 2$ and $K = 4$, (b) $M = 8$ and $K = 16$, and (c) $M = 32$ and $K = 64$ at both the transmitter and receiver

can hardly resolve multipath components accurately. Therefore, the technique may capture a local optimum which has a moderate, but not the highest, function value, causing a performance degradation. Fig. 3 demonstrates an example of the Nelder-Mead-based beam training technique implementing under a NLoS channel condition and outputting beam pairs: $P^1_{opt} = (1, 1)$, $P^2_{opt} = (15, 16)$ and $P^3_{opt} = (55, 62)$. However, the expected output points are $P^1_{opt} = (1, 1)$, $P^2_{opt} = (5, 14)$ and $P^3_{opt} = (53, 15)$.

Motivated by improving the performance robustness against NLoS channel models, modifications and extensions have been proposed to the Nelder-Mead-based beam training technique. Compared with the original version, the modified technique starts the training process using beams with higher resolution, i.e., $M_{m1} = 8$ and $K_{m1} = 16$ (see Fig. 3b). Moreover, a grouping scheme is applied to the $K_{m1} = 16$ beams at both transmitter and receiver in order to avoid the case that the non-convex objective function misdirects the trace of the global optimum.

Using the beamforming model described in Section IV-B, the optimal beam pair is found using the following procedures in NLoS scenarios, which are summarized in Algorithm 1:

1) Stage 1:

- Activate $M^1 = 8$ antennas and create $K^1 = 16$ beams using Equation 1; Index beams from the transmitter and receiver by p^1 and q^1 respectively.
- Apply a grouping scheme and divide the transmit and receive beams into N_g ($1 < N_g < K^1$) groups respectively.
- Iterate the operations from the first stage of the original beam training technique through the N_g^2 pairwise combinations of the beam groups; Each iteration starts with the point, $P^1_{1,(n_{ti},n_{ri})} = (p^1_{1,n_{ti}}, q^1_{1,n_{ri}})$:

$$\begin{aligned} p^1_{1,n_{ti}} &= floor(N_b/2) + 1 + N_b \times (n_{ti} - 1), \\ q^1_{1,n_{ri}} &= floor(N_b/2) + 1 + N_b \times (n_{ri} - 1), \end{aligned} \tag{6}$$

  where $n_{ti}, n_{ri} = 1, \cdots, N_g$, indexing the transmit and receive beam groups respectively. $N_b = floor(K^1/N_g)$ denotes the average number of beams in each group.
- Output the N_g^2 optimal beam pairs, $P^1_{opt,(n_{ti},n_{ri})} = (p^1_{opt,(n_{ti},n_{ri})}, q^1_{opt,(n_{ti},n_{ri})})$; Rank these beam pairs in decreasing order.

2) Stage 2:

- Quadruple active antennas along with beams at both transmitter and receiver, $M_2 = 32$ and $K_2 = 64$.
- Select the top N_c ($1 < N_c < N_g^2$) beam pairs given in the previous stage.
- Iterate the operations from the second stage of the original beam training technique for N_c times, each with the starting point, $P^2_{1,n_c} = (p^2_{1,n_c}, q^2_{1,n_c}), n_c \in [1, N_c]$:

$$\begin{aligned} p^2_{1,n_c} &= 2 \times (2 \times p^1_{opt,n_c} - 1) - 1, \\ q^2_{1,n_c} &= 2 \times (2 \times q^1_{opt,n_c} - 1) - 1, \end{aligned} \tag{7}$$

- Output the N_c optima, $P^2_{opt,n_c} = (p^2_{opt,n_c}, q^2_{opt,n_c})$ and rank them in decreasing order.

The top ranked optimum, $(p^2_{opt,1}, q^2_{opt,1})$, index a pair of beams with the given resolution which maximizes the received signal power and will be used for data transmission. The remaining $(N_c - 1)$ beam pairs are reserved as backups in case of a disconnection due to the human blockage [5], [12].

The selection of the value of N_g and N_c involves a trade-off between accuracy and complexity. The application of the grouping scheme amounts to splitting the objective function, formed with $K = 16$ beams at both transmitter and receiver, into N_g^2 cells. The value of N_g is chosen so that each cell has a convex surface with a single optimum. Also, the scheme of tracking the $N_c (N_c > 1)$ top ranked beam pairs solves the accuracy problem caused by unresolvable multipath components under NLoS channel conditions. However, both schemes increase the required number of measurement steps.

V. Simulation Results

This section presents simulation results to compare the performance of beamforming techniques adopted by 60 GHz WLAN/PAN systems [1], [2] and the ones based on the Nelder-Mead simplex method. The comparison is carried out in terms of search complexity, measured by the required steps of measurement, and the success probability, measured by the rate of the same selection performance achieved by the techniques and the exhaustive search under 500 channel realizations.

A. Simulation Configurations

1) System Model: A symmetric beamforming model is considered for software simulations, where both transmitter and receiver use the uniform linear array with $M = 32$ antennas and a separation of $\lambda/2$. Indoor channel models for 60 GHz WLAN systems (see section II-C) are respectively simulated under 500 LoS and NLoS conditions to evaluate the performance of the beamforming techniques.

2) Beam Patterns: For convenient comparison, the codebook design presented in section II is employed by all the beamforming techniques under evaluation, together with the assumptions shown below:

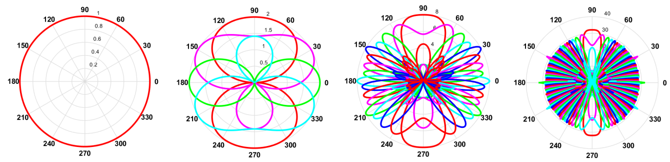
- For both "codebook-based protocol" and "iterative method", the $K = 64$ beams are equally mapped into 4 sectors; individual sector and beam have equivalent

Algorithm 1 The Modified Nelder-Mead-based Beam Training Technique

1: $j \leftarrow 1$
2: $M^1 \leftarrow 8 \quad p^1, q^1 \in C(M^1) \quad C \leftarrow$ Equation 1
3: $Opt^t \leftarrow [(0,0);(-1,0);(1,0);(0,-1);(0,1)]$
4: **for** $n_{ti} \leftarrow 1$ to N_g **do**
5: **for** $n_{ri} \leftarrow 1$ to N_g **do**
6: $P^1_{1,(n_{ti},n_{ri})} \leftarrow (p^1_{1,n_{ti}}, q^1_{1,n_{ri}})$ using Equation 6
7: **for** $sl \leftarrow -1, 1$ **do**
8: $p^1_{2^{sl},n_{ti}} \leftarrow p^1_{1,n_{ti}} + sl$
9: $Y^1_{2^{sl},(n_{ti},n_{ri})} \leftarrow f(p^1_{2^{sl},n_{ti}}, q^1_{1,n_{ri}})$ using Equation 3
10: $q^1_{3^{sl},n_{ri}} \leftarrow q^1_{1,n_{ri}} + sl$
11: $Y^1_{3^{sl},(n_{ti},n_{ri})} \leftarrow f(p^1_{1,n_{ti}}, q^1_{3^{sl},n_{ri}})$ using Equation 3
12: **end for**
13: $P^1_{2,(n_{ti},n_{ri})} \leftarrow (p^1_{2^{sl},n_{ti}}, q^1_{1,n_{ri}}) | max_{sl} Y^1_{2^{sl},(n_{ti},n_{ri})}$
14: $P^1_{3,(n_{ti},n_{ri})} \leftarrow (p^1_{1,n_{ti}}, q^1_{3^{sl},n_{ri}}) | max_{sl} Y^1_{3^{sl},(n_{ti},n_{ri})}$
15: Update the three vertexes using the Nelder-Mead simplex method to obtain $P^1_{con,(n_{ti},n_{ri})}$
16: **for all** Opt^t **do**
17: $P^1_{Opt^t,(n_{ti},n_{ri})} \leftarrow P^1_{con,(n_{ti},n_{ri})} + Opt^t$
18: $Y^1_{Opt^t,(n_{ti},n_{ri})} \leftarrow f(P^1_{Opt^t,(n_{ti},n_{ri})})$
19: **end for**
20: $P^1_{opt,(n_{ti},n_{ri})} \leftarrow P^1_{Opt^t,(n_{ti},n_{ri})} | max Y^1_{Opt^t,(n_{ti},n_{ri})}$
21: **end for**
22: **end for**
23: Rank $P^1_{opt,(n_{ti},n_{ri})}$ in order of decreasing link quality
24: $j \leftarrow j + 1$
25: $M^j \leftarrow M^{j-1} \times 4 \quad p^j, q^j \in C(M^j)$
26: **for** $n_c \leftarrow 1$ to N_c **do**
27: $P^j_{1,n_c} \leftarrow (p^j_{1,n_c}, q^j_{1,n_c})$ using Equation 7
28: **for** $sl \leftarrow -2, 2$ **do**
29: $p^j_{2^{sl},n_c} \leftarrow p^j_{1,n_c} + sl$
30: $Y^j_{2^{sl},n_c} \leftarrow f(p^j_{2^{sl},n_c}, q^j_{1,n_c})$ using Equation 3
31: $q^j_{3^{sl},n_c} \leftarrow q^j_{1,n_c} + sl$
32: $Y^j_{3^{sl},n_c} \leftarrow f(p^j_{1,n_c}, q^j_{3^{sl},n_c})$ using Equation 3
33: **end for**
34: $P^j_{2,n_c} \leftarrow (p^j_{2^{sl},n_c}, q^j_{1,n_c}) | max_{sl} Y^j_{2^{sl},n_c}$
35: $P^j_{3,n_c} \leftarrow (p^j_{1,n_c}, q^j_{3^{sl},n_c}) | max_{sl} Y^j_{3^{sl},n_c}$
36: Update the three vertexes using the Nelder-Mead simplex method to obtain P^j_{con,n_c}
37: Repeat step $16-20$ to obtain P^j_{opt,n_c}
38: **end for**
39: Rank P^j_{opt,n_c} in order of decreasing link quality

resolutions to beam patterns created using Equation 1 with $M = 8$ and $M = 32$ respectively, as illustrated in Fig. 4c and Fig. 4d.

- The "iterative method" activates a single antenna to create the quasi-omni pattern required in the SLS phase, as shown in Fig. 4a.
- The "codebook-based protocol" creates the quasi-omni patterns using Equation 1 with $M = 2$, as illustrated in Fig. 4b.



(a) (b) (c) (d)

Fig. 4: Beam patterns created using Equation 1 with (a) $M = 1$ and $K = 1$, (b) $M = 2$ and $K = 4$, (c) $M = 8$ and $K = 16$ and (d) $M = 32$ and $K = 64$ at both the transmitter and receiver

TABLE I: Performance Evaluation for LoS Scenarios

Parameters	Value
Number of antenna elements M	32
Number of beams K	64
Number of channel realizations	500
Distance between TX and RX [m]	3
Nelder-Mead algorithm coefficients $\alpha/\gamma/\beta$	1.0 /2.0 /0.5

3) Simulation parameters: For performance evaluations under both LoS and NLoS channel conditions, simulation parameters are listed in Table I.

B. Performance Evaluation for LoS Channel Conditions

Table II summarizes the success probability (P) and search complexity (C) evaluated for all beamforming techniques under 500 LoS channel realizations. The "iterative method" provides the highest success probability, 100%, while requiring the highest search complexity, i.e., 144 steps of measurement: 16 (SLS)+2×64 (BRP). In contrast, the "codebook-based protocol" requires only 48 steps: 16 (DEV-to-DEV linking)+16 (sector-level searching)+16 (beam-level searching), which is a third of that needed by the "iterative method". However, it gives a success probability of only 75.8%. By requiring only 36 search steps on average and achieving a success probability of 99%, the original Nelder-Mead-based beam training technique provides the best trade-off in terms of the accuracy and complexity. Its modified counterpart, with $N_g = 3$ and $N_c = 1$, however, gives a success probability of 98.4% while requiring 137 steps on average.

C. Performance Evaluation for NLoS Channel Conditions

For NLoS channel models, the beamforming techniques suffer from a performance degradation due to the lack of a direct path between the transmitter and receiver. Table III shows the simulation results. The decrease in success probability is 32.8%, from 100% to 67.2%, for the "iterative method", while 32% for the "codebook-based protocol". As for the Nelder-Mead-based beam training technique, a success probability of only 56.4% is provided. Fortunately, the modifications on this Nelder-Mead-based technique effectively improve the performance robustness in NLoS channel conditions. With $N_g = N_c = 3$, this technique increases the success probability from 56.4% to 87.6%, compared to its unmodified counterpart, which, however, comes at a price of consuming 119 more search steps.

Table IV demonstrates the impact of technique parameters N_g and N_c on the success probability and search complexity. By increasing either N_g or N_c, improvements on both accuracy and complexity will be observed. Changing N_g from 3 to 4, with $N_c = 3$, gives rise to an increase of 4.8% on the

TABLE II: Performance Evaluation for LoS Scenarios

BF techniques	P	C		
		min	ave	max
Iterative method	100%	144	144	144
Codebook-based BF	75.8%	48	48	48
Nelder-Mead-based BF	99%	30	36	44
M-Nelder-Mead-based BF	98.4%	118	130	159

TABLE III: Performance Evaluation for NLoS Scenarios

BF techniques	P	C		
		min	ave	max
Iterative method	67.2%	144	144	144
Codebook-based BF	43.8%	48	48	48
Nelder-Mead-based BF	56.4%	30	35	42
M-Nelder-Mead-based BF	87.6%	133	154	178

TABLE IV: Effects of Simulation Parameters

Technique Parameters	P	C		
		min	ave	max
$N_g = 3$ and $N_c = 1$	75%	110	129	152
$N_g = 3$ and $N_c = 3$	87.6%	133	154	178
$N_g = 4$ and $N_c = 3$	92.4%	190	209	231

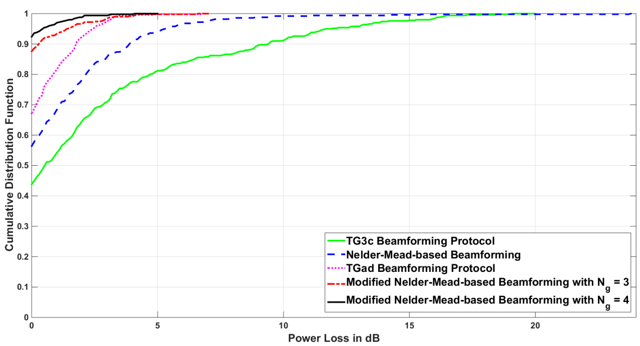


Fig. 5: CDF of the power loss between the evaluated beamforming techniques and the exhaustive search under NLoS channel conditions

success probability, with an increase of 80 steps on the search complexity. For the case where N_c is changed from 1 to 3, with $N_g = 3$, the increase on the success probability is 12.6%, with 23 steps increase on the search complexity.

It is also useful to compare power loss performance between techniques since in some cases the selection of a non-optimal beam pair may not have a significantly detrimental effect. Figure 5 shows the cumulative distribution function (CDF) of the power loss between the evaluated beamforming techniques and the exhaustive search under NLoS channel conditions. With $N_g = N_c = 3$, the modified Nelder-Mead-based beam training technique suffers a power loss smaller than 1dB with a possibility of 93.4%, while requiring 154 steps of measurement on average. This technique also provides backup antenna weight coefficients which can be utilized to maintain a viable link in the event that the current weights suddenly degrade, e.g, due to blockage. Another promising technique is the "iterative method" which gives a slightly lower possibility of 81.6%, and a reduced search complexity of 144 steps. This method requires perfect quasi-omni patterns, as shown in Fig 4a. However, the quasi-omni patterns cause extra erroneous beam selections [5], particular in NLoS scenarios.

VI. Conclusion

In this paper, an efficient codebook-based beam training technique is proposed for mmWave communication systems. By formulating the beam training process as a multi-stage combinational optimization problem, the proposed technique finds the optimal beam pair using the Nelder-Mead simplex method. Moreover, it achieves a desirable trade-off between the training accuracy and complexity by adjusting the value of certain parameters. Compared with beamforming protocols adopted by 60 GHz WLAN/PAN standards, the technique improves the performance robustness against NLoS channel models. Simulation results show that with large antenna arrays employed at both transmitter and receiver, the proposed technique provides a power loss less than 1dB compared with the exhaustive search at a rate of 93.4%.

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